Efficient Electro-Optic Sampling Detection of Terahertz Radiation via Cherenkov Phase Matching

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Abstract

We experimentally demonstrate an efficient electro-optic (EO) sampling scheme based on Cherenkov phase matching of broadband terahertz radiation with 800-nm femtosecond probe beam in a 0.5 mm-thick $LiNbO_3$ (LN) crystal coupled to a Si prism. Compared with standard EO sampling using collinear phase matching in a 4 mm-thick ZnTe crystal, the EO signal from a Cherenkov-phase-matched LN crystal was larger by a factor of 2.5. The Cherenkov phase matching technique can be achieved with any probe wavelength and hence has an advantage over the collinear phase matching method.

Cherenkov radiation mechanism is an established way to achieve phase matching between an ultrashort optical pulse and terahertz waves in an electro-optic material with large collinear velocity mismatch, such as $LiNbO_3$ (LN) [1, 2]. To produce a Cherenkov cone of terahertz waves, the optical pulse should be focused to a size of the order of or smaller than the terahertz wavelength. Phase matching is achieved between the moving optical pulse and a plane terahertz wave propagating under a certain angle to the laser path.

In recent years, several improvements of this technique have been developed. In particular, to minimize strong terahertz absorption in LN, it was proposed to align the laser beam parallel with and near the lateral surface of the LN crystal and put, additionally, a Si-prism coupler on the surface to output the Cherenkov radiation from the crystal [3]. The most up-to-date generation scheme is based on using a thin LN layer attached to a Si-prism (or sandwiched between the prism and a substrate) [4,5]. The structure provides guiding of the pump laser pulse in the LN layer over a long distance, thus, preventing the diffraction distortion of the pulse and increasing the interaction length between the laser pulse and terahertz radiation. This results in a corresponding increase in terahertz emission. Using such a scheme with 8 mm long Si–LN–BK7 structure (with 30-50 μm thick LN layer), Ti:sapphire laser pulses of relatively low energy (~40 μJ) were converted into terahertz pulses of ~3 THz bandwidth with efficiency over 0.1% [6]. In the similar structure with a thin (of 3.8 μm thickness) layer of MgO-doped LN sandwiched between a Si prism and undoped LN [7], a quasi-continuous terahertz radiation tunable in a wide frequency range 0.1-7.2 THz was generated with 10^{-5} % efficiency via difference frequency generation process. Another promising way to achieve noncollinear phase matching between the laser pulse and terahertz waves in the materials with large velocity mismatch, similar to Cherenkov mechanism, is using tilted-pulse-front pumping (for recent review of this method, see, for example, Ref. [8]).

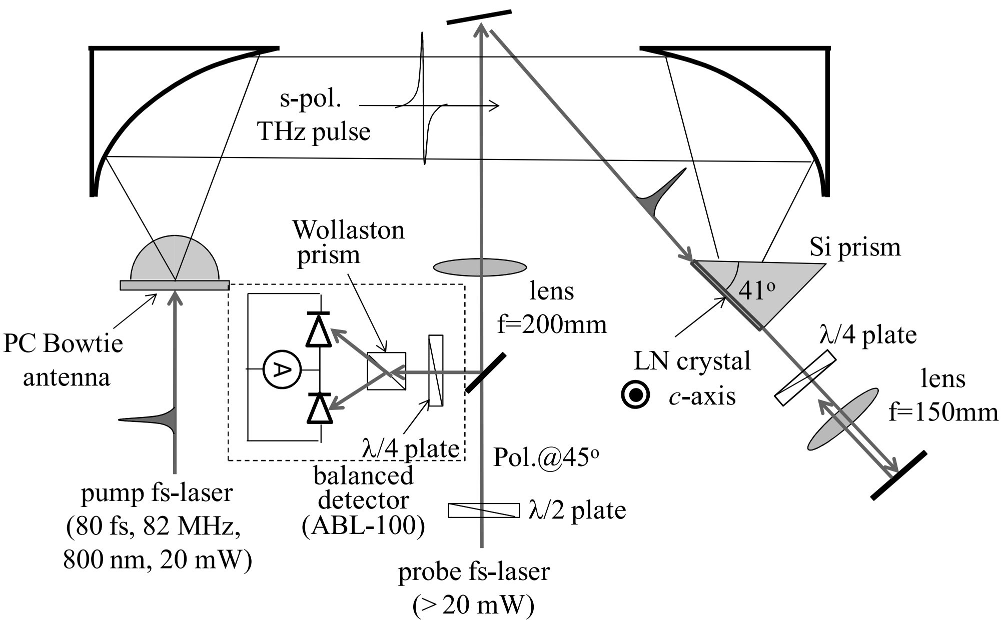

Fig. 1. Schematic of the experimental setup.

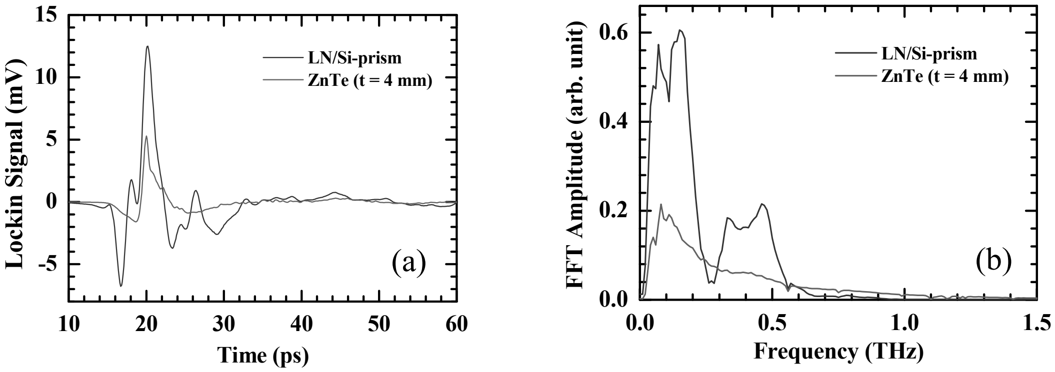

Fig. 2. (Color online) (a) Terahertz waveforms measured with the Si-LN structure (solid) and with a ZnTe crystal (dashed). (b) Corresponding Fourier spectra.

In the present paper, we demonstrate experimentally that Cherenkov phase matching mechanism can be also used for efficient electro-optic (EO) sampling of broadband terahertz pulses. Using a 0.5 mm-thick LN crystal attached to a Si prism we obtained a 2.5 larger EO signal than in a standard collinear sampling technique with ZnTe crystal.

Figure 1 shows the schematic of the experimental setup. The experiment was performed with a Ti:sapphire laser (800 nm wavelength, 80 fs pulse duration, and 82 MHz repetition rate) as a light source. The laser pulses were split into pump and probe beams. The pump beam of 20 mW average power triggered a photoconductive bowtie antenna on a low-temperature-grown GaAs substrate, which was biased with an alternating ±50 V voltage. A hyper-hemispherical Si lens of a 13 mm diameter was used to outcouple generated terahertz radiation from the substrate to the free space. The terahertz beam was collimated and focused onto a LN crystal through a right triangular high-resistivity-Si prism by a pair of parabolic mirrors (50 mm diameter and 76 mm focal length). The prism was cut at the Cherenkov angle 41° [4] (another apex angle is 49°), and the incident terahertz beam was aligned along the normal to the prism face (Fig. 1). The 1% MgO-doped stoichiometric LN crystal, bonded to the prism bottom surface, had a 0.5 mm thickness and 10 × 5 mm lateral dimensions (the same as of the prism bottom surface). The *c*-axis of the LN crystal was oriented perpendicularly to the triangular face of the prism, and the polarization of the terahertz radiation was aligned parallel to the *c*-axis. The probe laser beam (20 mW power) was focused onto the 10 × 0.5 mm facet of the LN crystal by a 200 mm focus lens. The polarization of the beam was at 45° to the *c*-axis of the LN crystal. This polarization was electro-optically modulated by the terahertz field inside the LN crystal. To compensate the parasitic transformation of the polarization due to birefringence of the LN crystal, the probe beam was sent through a quarter wave plate, then it was reflected back by a mirror and went through the same quarter wave plate and the LN crystal again (a 150 mm focus lens was used for collimation) [9]. Changes in polarization were measured by a balanced photodetector (ABL-100, Zomega Corp.) with its output signal fed to a lock-in amplifier; the alternating bias voltage of the terahertz emitter was used as a reference signal for the amplifier.

Figure 2(a) shows the terahertz waveforms measured with the Cherenkov-phase-matched LN crystal (Si-LN structure) and, for comparison, with a 4 mm-thick ZnTe crystal. The corresponding spectra are shown in Fig. 2(b). It is seen from Fig. 2(a) that the peak value of the EO signal from the Si-LN structure is 2.5 times larger than that from the ZnTe crystal. In the signal from the Si-LN structure, the peak is followed by fading oscillations that can be attributed to multiple reflections of the terahertz waves from the boundaries of the LN crystal. Correspondingly, the spectrum for the Si-LN structure has prominent undulations [Fig. 2(b)].

In the standard collinear EO detection scheme, the signal from a LN crystal is much weaker than that from a ZnTe crystal due to a large velocity mismatch between the probe optical pulse and terahertz waves in LN [10]. Indeed, the terahertz phase refractive index n_{THz} of LN is more than two times larger than its optical group refractive index n_{g} (n_{THz} = 4.75 at the 0.5 THz frequency and n_{g} = 2.23 at the 800 nm optical wavelength) [8,11]. Therefore, the coherence length $L_{\mathrm{c}}(\nu) = c(2\nu|n_{\mathrm{THz}}(\nu) - n_{\mathrm{g}}|)^{-1}$ [12] is as small as ~120 μm at the frequency ν = 0.5 THz and 800 nm optical wavelength. Using the Si-LN structure allows one to compensate the large velocity mismatch between the optical probe and terahertz pulses. Since the conventional coherence length is inadequate for characterization of the noncollinear terahertz-optical interaction in the Si-LN structure, we introduce new coherence length

$$L_{\mathrm{c}}(\nu) = \frac{c}{2\nu\left|n_{\mathrm{Si}}\cos\beta - n_g\right|}, \tag{1}$$

where n_{Si} is the terahertz phase refractive index of the Si prism and β the crossing angle of the terahertz and optical probe beams. The perfect phase matching ($L_{\mathrm{c}} \to \infty$) is achieved at $\cos\beta = n_g/n_{\mathrm{Si}}$. Using n_{Si} = 3.418, we obtain β = 49.3°, and, therefore, the optimal apex angle of the prism is 90° - 49.3° = 40.7°. Figure 3 shows the dependence $L_{\mathrm{c}}(\nu)$, calculated using Eq. (1), for different β. According to Fig. 3, even for an essential detuning of β from the optimal angle 49.3° the Si-LN structure provides orders of magnitude larger coherence length L_{c} as compared to the standard

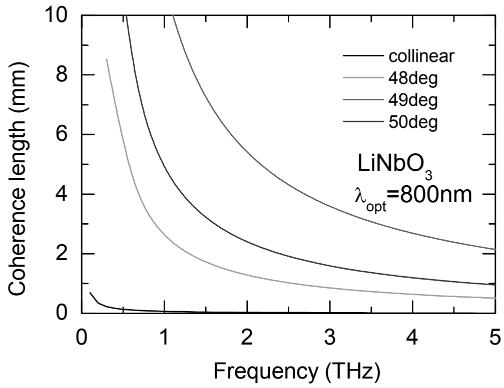

Fig. 3. Coherence length L_c defined by Eq. (1) as a function of terahertz frequency ν for β = 48°, 49°, and 50° at 800 nm wavelength.

collinear scheme in a LN crystal.

When a perfect phase matching is achieved, the differential phase retardation $\delta\varphi(\tau)$ experienced by the probe beam in the LN crystal of the Si-LN structure due to the terahertz field $E_{\mathrm{THz}}(\tau)$ over a distance L can be presented as [10]

$$\delta\varphi(\tau) = \frac{\omega_{\mathrm{opt}}}{2c}(n_{\mathrm{e}}^3 r_{33} - n_{\mathrm{o}}^3 r_{13}) E_{\mathrm{THz}}(\tau) L \,, \tag{2}$$

where τ is the time delay between the probe and terahertz pulses, n_{o} and n_{e} are the refractive indices of the probe's ordinary and extraordinary rays, respectively, r_{13} and r_{33} are the EO coefficients, and ω_{opt} is the optical probe angular frequency. According to Eq. (2), we define the figure of merit of the Si-prism coupled LN crystal for EO sampling as

$$\mathrm{FOM}_{\mathrm{LN}} = \frac{1}{2}\left(n_{\mathrm{e}}^3 r_{33} - n_{\mathrm{o}}^3 r_{13}\right). \tag{3}$$

Substituting into Eq. (3) $n_{\mathrm{o}} = 2.255$ and $n_{\mathrm{e}} = 2.176$ at 800 nm, $r_{13} = 9.6$ pm/V and $r_{33} = 30.9$ pm/V [13], we obtain $\mathrm{FOM}_{\mathrm{LN}} \approx 104$ pm/V.

For the collinear EO sampling in a <110>-cut ZnTe crystal of thickness L, the differential phase retardation is given by [10]

$$\delta\varphi(\tau) = \frac{\omega_{\mathrm{opt}}}{c} n_{\mathrm{opt}}^3 r_{41} E_{\mathrm{THz}}(\tau) L \,, \tag{4}$$

where n_{opt} is the optical refractive index and r_{41} the EO coefficient of ZnTe. The corresponding figure of merit

$$\mathrm{FOM}_{\mathrm{ZnTe}} = n_{\mathrm{opt}}^3 r_{41} \tag{5}$$

is estimated as $\mathrm{FOM}_{\mathrm{ZnTe}} \approx 96$ pm/V by using $r_{41} = 4.04$ pm/V and $n_{\mathrm{opt}} = 2.87$ at 800 nm [8]. Comparing $\mathrm{FOM}_{\mathrm{LN}}$ and $\mathrm{FOM}_{\mathrm{ZnTe}}$, one can conclude that EO sampling efficiency is expected to be similar with the Si-LN structure and a ZnTe crystal for the same interaction length L.

In our experiment, the interaction length for the Cherenkov-phase-matched LN crystal was determined by the focal spot size of the terahertz beam in the LN crystal rather than the crystal length. The lateral focal spot size of the terahertz beam in the LN crystal can be estimated as

$$L = 1.22 \frac{\lambda_{\mathrm{THz}}}{n_{\mathrm{Si}}} \frac{f}{b} \frac{1}{\cos\beta} \sim 4 \text{ mm}, \tag{6}$$

where we used the focal length of the parabolic mirror $f = 76$ mm, the effective terahertz beam radius $b = 15$ mm, $\beta = 49°$, and the terahertz wavelength $\lambda_{\mathrm{THz}} \sim 1.5$ mm corresponding to the central frequency $\nu \sim 0.2$ THz of the spectrum in Fig. 2(b). For a ZnTe crystal, the interaction length can be limited, in principle, either by the crystal thickness or by the coherence length L_{c}. For the 800 nm-wavelength light and terahertz frequencies less than 0.5 THz [Fig. 2(b)], the coherence length L_{c} exceeds 4 mm [12]. Therefore, the interaction length for the ZnTe crystal, used in the experiment, was limited by the crystal thickness $L = 4$ mm. Thus, the interaction lengths for the Si-prism-coupled LN crystal and ZnTe crystal were practically the same and, therefore, the EO sampling efficiencies in the two cases should relate as $FOM_{LN}/FOM_{ZnTe} \sim 1$.

To explain the larger ratio (~2.5) of the efficiencies observed in the experiment, let us take into account different terahertz absorption in LN and ZnTe crystals and different reflection at the surfaces of the crystals. The terahertz absorption on the half-thickness of the LN crystal (0.25 mm) is less than 3% for $\nu < 0.5$ THz [11], while the absorption on the half-thickness of the ZnTe crystal (2 mm) is ~5% [14]. The amplitude reflection loss for the Si prism-coupled LN crystal is higher by 3% than that for the ZnTe crystal (for the estimation, we used the refractive index ~4.75 for LN [11] and 3.15 for ZnTe [14] at $\nu = 0.2$ THz). These reflection and absorption losses cannot explain the large difference in the efficiency of the EO sampling with the Si-LN structure and the ZnTe crystal. For the moment, we do not have any reasonable explanation for the discrepancy from the expected efficiency ratio based on the FOM.

To conclude, we have demonstrated efficient EO sampling of broadband terahertz radiation in the Cherenkov phase matching scheme with a Si-prism-coupled LN crystal. The signal magnitude was about 2.5 times larger than that from a 4 mm-thick ZnTe crystal in a standard collinear phase matching scheme. Our results put forward the Cherenkov phase matching mechanism as a useful tool not only for generation but also for detection of broadband terahertz radiation. An essential advantage of the Cherenkov phase matched EO sampling technique is its feasibility at different laser wavelengths. In particular, this technique can be conveniently implemented with a compact 1.55-μm femtosecond fiber laser.

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